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ENVIRONMENTAL FACTORS AFFECTING CORROSION OF PIPELINE STEEL: A REVIEW

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ABSTRACT

Carbon steel is widely used as pipeline materials in transporting petroleum products from one region to another. However, the pipeline systems are often corroded due to environmental factors which affect the pipeline integrity. Atmospheric corrosion of carbon steel pipeline materials is influenced by many environmental factors which increase the corrosion rate of these steel materials when in operation in different coastal regions. Experiments have been used to investigate the impacts of some of the environmental factors on the corrosion of several carbon steel materials. However, due to cost and time consumption of this process, numerically analyses have been used to complement the understanding of the corrosion process.This paper reviews the latest studies on the impact of environmental factors on corrosion of some carbon steel materials used in the petroleum industry. Some important experimental procedures and results of works done in relation to environmental factors on steel materials are discussed.The review will allow many manufacturers, designer and operators of pipeline carbon steel materials to consider the effect of each environmental factor on the pipeline material and select a better carbon steel material that can withstand the effect of the prevailing environmental factors on the pipeline system.

KEYWORDS: Carbon Steel, Environmental Factors, Hydrogen Sulphide, Temperature, Pipeline

INTRODUCTION

Carbon steels are mostly used in the transportation of oil and gas from one region to another due to its cost effectiveness and applications [1, 2]. Regrettably, corrosion of carbon steel still occurs due to contact between the transporting medium and the environmental factors. It was reported that erosion-corrosion process that occurs during transportation of petroleum products through pipeline may be an important factor in the failure of the pipeline system[3]. However, environmental factors can be influential in the overall corrosion of carbon steel pipeline and need to be understood.

Environmental parameters such as; SO_2, H_2S and particulates of sea salt, humidity, temperature, contaminants and rainfall can vary from one region, or country to another and often involves chemical and electrochemical reactions[4-10]. These parameters influence the corrosion of steel materials especially when the metals are in operational condition [1, 11-14]. However, the effect of environmental factor on the corrosion mechanism of carbon steel commonly used in oil and gas transportation has not yet been detailed in literature. Lan et al. [8] studied the concentration of some environmental factors in Vietnam, considering the effect of country's high temperature, relative humidity and frequent rainfall on carbon steel. The concentration of sulphur dioxide (SO_2) was found to be high in this country compared to other environmental

factors. The result revealed that the steel was very sensitive to acidic pollutants especially sulphur dioxide and acid rains [8]. Despite the different technique that have been used to reduce the corrosion rate of carbon steel in pipeline systems, this destructive phenomenon is still observed and believed to be affected by the environmental factors and the carbon steelused inthe design of the pipeline. Understanding the effect of environmental factors on the corrosion mechanism of pipeline carbon steel used in the oil and gas transportation becomes necessary. For a coastal region like Qatar where the temperature is around 50°C between July and October with high humidity, the temperature and other environmental factors may have influential roles in the corrosion process, especially during the transportation of oil and gas in sour environment.Environmental factors can change from one country to another as some countries have high temperature, high humidity, frequent rainfall, and several pollutants availability [15]. These factors will subsequently influence the corrosion behaviour of pipeline carbon steelin operation in a given location. Knowledge of the environmental pollutants is important for better understanding and management of the corrosion damage being experience in the petroleum industry. Furthermore, detailed review ofthe effects of atmospheric environmental factors on pipeline materialsis lacking. This review aimed at filling this gap by addressing each of the environmental factor in relation to corrosion of carbon steel material.

ENVIRONMENTAL FACTORS AFFECTING THE CORROSION OF PIPELINE CARBON STEEL

There are several environmental factors that influence carbon steel materials exposed to the atmosphere. The degree of impact of these factors on the exposed materials depends on the intensity and concentration of these factors at each location and can also be a combined effect of interrelated environmental factors on the carbon steel.

Effect of Sea Water Salt on the Corrosion of Corrosion of Carbon Steel

Chloride ions are often found in industrial areas and exist as one of the most vital and common atmospheric corrosive agent[16, 17].The presence of the chloride ions in the atmosphere can influence the corrosion of carbon steel pipeline exposed to atmospheric condition and may lead to the failure of the entire pipeline system [18-20]. In atmospheric corrosion process of carbon steel pipeline, corrosion is initiated by droplets of atmospheric water mostly from the sea shore, coupled with residual stress imposed on the pipeline system due to transportation of petroleum products, which often results in chloride-induced SCC [21]. Several studies have been carried out on the corrosion behaviour of different steel materials exposed in chloride environment [22-24]. The general understanding is that the corrosion rate of carbon steel material increases after exposure to chloride contaminated atmospheric condition for certain period. Castaño et al. [9] studied the effect of chloride on the corrosion behaviour of carbon steel at six test sites in Colombia with emphasis on the relationship between the exposure time and environmental characteristics of each site. Chlorides were found to be most influential environmental factor affecting the corrosion of material in the stations. In a similar study, Ma et al. [5] studied the effect of Cl^- ion on the atmospheric corrosion rate of carbon steel. In other to compare the marine effect with other atmospheric environment on the sample material, distances of 95 and 375 m from the sea line were considered for the carbon steel corrosion test after exposure to the atmosphere for 24 months.

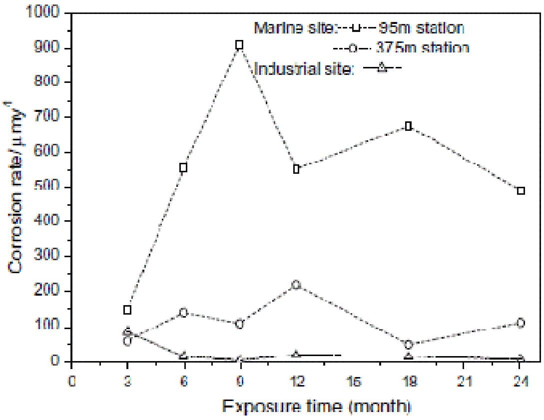

Figure 1: Corrosion Rate of Carbon Steel in Different Atmosphere Conditions [5]

On examination of the steel sample, the result revealed that Cl^{-} ion influenced the corrosion rate, morphology and composition of the carbon steel material as shown in Figure 1.

Sea salt water is commonly used in many applications as sodium chloride and calcium chloride and has been dated back to early centuries. The usage has associated amount of damage to some structures existing within the atmospheric environment as reported by several researchers [25-28]. Sea salt has been reported as one of the predominant environmental contaminant that corrode carbon steel pipeline especially in the coastal areas where the sea salt concentration is relatively high [29]. Syed [29] pointed out that sea wind can release up to 100lb of sea salt per cubic mile into the air. Hasan et al. [30] showed that under a highly-conducting electrolyte, such as sea-water, effective corrosive areas will be greater, and severe corrosion may occur on the carbon steel metal resulting in high corrosion rate. Detailed study on the effect of atmospheric salinity on the corrosion of carbon steel byAlcántara et al. [31], considering the variation in corrosion of pipeline carbon steel with the distance from the sea shore displayed in Figure 2, showed that corrosion rate of exposed carbon steel at a station near the sea shore line has the highest corrosion rate. The high corrosion rate was due to production of saline droplets on the exposed pipeline carbon steel from the sea and concentration of the chloride as have been reported elsewhere in the literature[32].

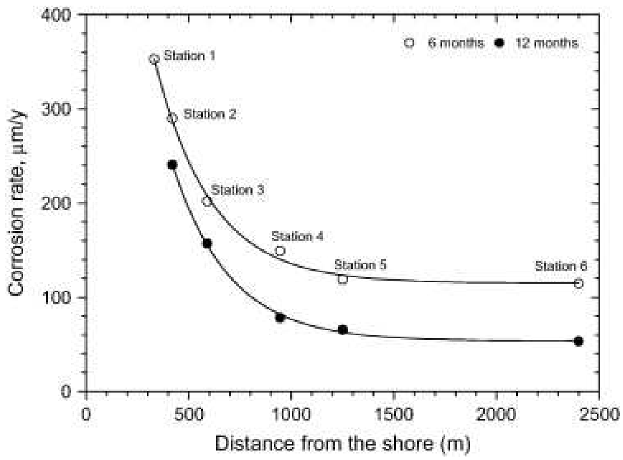

Figure 2: Variation in The Corrosion Rate of Carbon Steel With Distance from the Shore [31]

Other researchers have also shown that the sea-salt contain some quantities of magnesium chloride and sodium chlorides which corrode the pipeline carbon steel at low humidity [33, 34]. Ericssion [34]revealed that significant quantity of SO_2 is contained in sea salt water and can as well aggravate the corrosion rate of carbon steel. Another result from his study showed that combination of SO_2 and sea salt water increased the corrosion rate several times more than the contribution of individual constituent [34].

Effect if Sulphide Dioxide on Corrosion ofSteel Materials

Sulphur dioxide (SO_2) in addition to other environmental pollutants is one of the dominant constituents affecting the corrosion rates of carbon steels exposed to atmospheric condition[35-37]. Misawa et al.[38] attemptedto explain the basis electrochemistryof sulphur dioxide and corrosion of steel materials in 1974. The effort of understanding the mechanism of atmospheric corrosion of steel materials was supported by group researchers[37] in 1997, where the aggressiveness of SO_2 on carbon steel materials wereexplored and detailed. Several studies have been conducted on the effect of atmospheric SO_2 pollution on steel materials [7, 39, 40].Leygraf et al. [41] reported that significant amount of SO_2 deposited on the surface of carbon steel can result in formation of protective layer. The result further revealed that increased amount of the SO_2 can cause acidification of the aqueous layer, resulting in material anodic dissolution [41]. Other researchers have shown that corrosion of carbon steel materials due to presence of $SO_2$is an integral contribution of other parameters [42]. On the other hand, Zhang et al. [43]attributed the decrease in the corrosion rate of $SO_2$to gradual compact corrosion layer formation when the steel was exposure to atmosphere. The results further showed that increase in SO_2concentrationaccelerated the carbon steel corrosion rate.It has been reported that the concentration of SO_2 in the atmosphere may be more in the coastal areas [35], and consequently will affect the corrosion rate of the pipeline more in this area.In a moist environment, the SO_2 is absorbed by the pipeline carbon steel which is converted to $FeSO_4$. This process occurs because sulphur dioxide has a high solubility in water and has the affinity to form sulfuric acid in the atmospheric moisture films. In this process, sulphur ion according to equation 1 isformed as the product of sulphur dioxide oxidation.

$$SO_2 + O_2 + 2e^- \longrightarrow SO_4^{2-} \quad (1)$$

The formed sulphide ion from equation 1, acts as an active corrosion agent for further reaction. Syed[29] revealed that the presence of this ion in steel results in formation of iron sulphide which is a known corrosive product found on the steel surfaces exposed to atmosphere. The formed corrosion product is further hydrolysis to form ferric hydroxide which forms hydrogen sulphide, resulting in acidic corrosive medium [40, 44, 45].

Studies have shown that the reaction of significant quantity of the formed $FeSO_4$ from SO_2 and corrosion product provides a conducive environment for effective electrochemical process [46]. Furthermore, Aggressive anions such as SO_4^{2-} initiate the localized attack of the pipeline carbon steel materials. Recently, Wenjuan et al. [35] showed that the corrosion rate of the carbon steel initially increases with increasing SO_2 concentration and decreases with further increase in the SO_2 concentration. Similar result was observed by Knotkova et al. [47] in a 3-year tests, where it was observed that the corrosion of the steel material increased due to increasing SO_2 constituent in the atmosphere as shown in Figure 3.

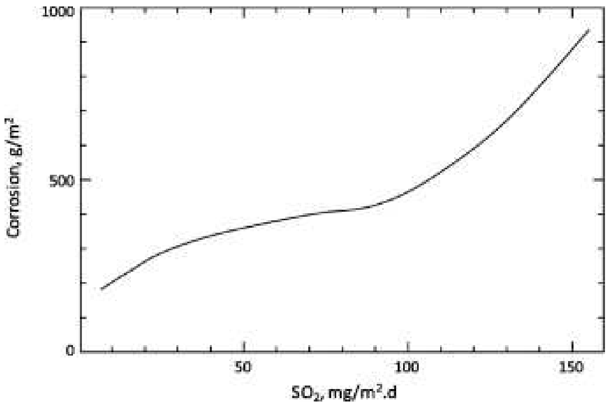

Figure 3:Corrosion of Carbon Steel in Outdoor Atmospheres as a Function of SO_2Pollution Level [47]

However, since some of these factors are predominantly in the atmosphere and act on several materials exposed to the atmosphere, it becomes possible that the rate at which each of the factor affects the pipeline carbon steel exposed to the atmosphere depends on the geographical region, microstructure of the pipeline carbon steel and intensity of each contributing factor.Based on the above reviews, it could be suggested that carbon steel manufactured for pipeline application should have some resistance to environmental chlorides and other environmental factors.

Effect of Hydrogen Sulphide on Corrosion of Carbon Steel Materials

In the oil and gas industry, sulphide ion is often produced by the sulphate reducing bacteria (SRB), through metabolism process[48-50]. Efforts have been made in understanding the effect of these bacteria (SRB) on pipeline carbon steel because of their roles in the petroleum industry[51, 52]. Most of the studies have focused on the activities of these bacteria in corrosion of carbon steel materials [49, 50]. Interestingly, the results have shown that sulphate reducing bacteria (SRB) influence the pipeline failure through cracking of pipeline material [53].In April 2004, Abedi et al. [53] studied the corrosion behaviour of X52 pipeline material in northern part of Iran. The result showed that the surface of the coated pipeline was disbanded, thereby exposing the pipeline material to surrounding atmospheric condition. The exposed material condition necessitates the electrochemical reaction between the environmental factors and the carbon steel materials, resulting in carbonate–bicarbonate solution formation. It was observed that sulphate reducing bacteria (SRB) activities increased the corrosion rate and related cracking process observed on the corroded steel surface [53].Other researchers have shown that when the pipeline carbon steel are exposure to sour environments, H_2S corrosion takes place on the steel material causing metal dissolution and corrosion pit formation [53]. As part of the corrosion process, hydrogen cathodically evolves on the metal surface and migrates into the steel material leading to metal embrittlement. It is well known that the corrosion pits are usually the initiation site for the main sulphide stress cracking at the metal surface. The main crack propagates by connecting the micro cracks in the metal, causing crack propagation and consequent pipeline failure at applied stress well below the material's yield strength. In another study, Fatah et al. [54] investigated the corrosion behaviour of X52 pipeline material after corrosion test, using scanning electron microscopy (SEM). The results revealed that increasing the concentration of sulphide ion increased the corrosion rate of X52 steel as shown in Figure 4.

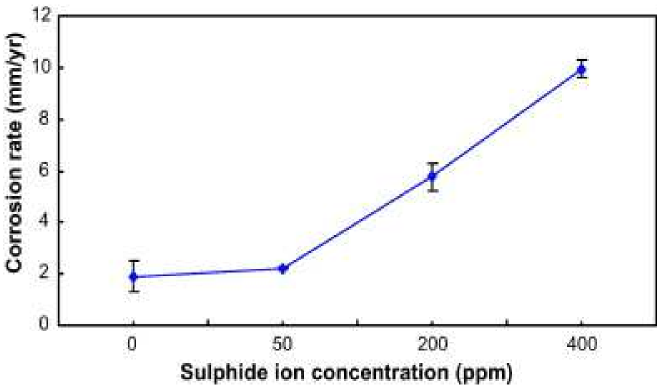

Figure 4: Effect of Sulphide on the Corrosion rate of Carbon Steel Material in 3% Solution [54]

In similar studies carried out by Newman et al. [55] and Kuang et al. [56] on corrosion of carbon steel pipeline materials revealed that similar corrosion rates were obtained for inorganic sulphide and sulphate reducing bacteria tests. It was found that the electrochemical corrosion behaviour of carbon steel was influenced by the concentration of sulphide ion generated by the SRB metabolism. In contrast, Dominique et al. [57] proposed that most corrosion process are electrochemical in nature, pointing out that the cathodic depolarization theory is not sufficient enough to explain the corrosion mechanism caused by SRB, since the theory does not include other factors such as carbon dioxide (CO_2), that assist in the microbiology corrosion process. It therefore implies that in atmospheric corrosion process, corrosion of carbon steel is influenced by combined action of interrelated factors [58].Nevertheless, for carbon steel pipeline materials of different microstructures, the effects of these interrelated factors might be different and failure mechanisms may be different. Fatah et al. [59] investigated the effects of sulphide ion on corrosion behaviour of X52 steel in simulated solution containing metabolic product species. The results showed that increasing the sulphide ions to a certain limit of 50ppm increased the corrosion rate of X52 steel. When the sulphide ion concentration was increased between 200 and 400 ppm sulphide, the corrosion rate decreased and was attributed to initial cathodic reaction in the presence of sulphide with further corrosion protection due to FeS film formation. Caines et al.[60] reported that Pitting can result in catastrophic consequences in pipeline system, since smaller pits can provide the initiation site for stress corrosion cracks as observed in Figure 5.

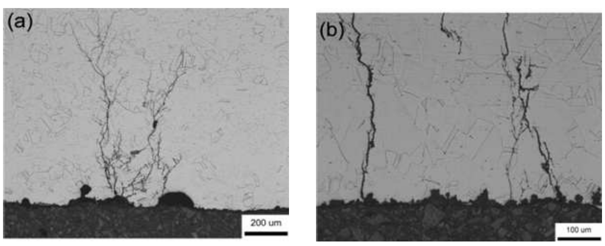

Figure 5: Transgranular Crack From External to Internal Surface of the Carbon Steel Material and (B) Transgranular Cracking on Inner Surface of the Same Carbon Steel Material [60]

The direction of propagation was evident from the crack direction as shown in Figure 5a. EDX analysis of the corroded steel material within the externally initiated crack showed a strong indication of sulphur. Recently, Roffey et al. [61] studied the effect of hydrogen sulphide on the stress corrosion cracking and non-stress corrosion cracking on the pipeline steel material. The result showed that several cracks were observed on the steel material for stressed and non-stressed carbon steel materials due to presence of sulphur in the corrosion medium.

Effect of Temperature on the Environmental Corrosion of Carbon Steel Materials

Temperatures of the surface water and other materials exposed to atmosphere have shown to have some relationship with latitude and humidity of the atmospheric condition [62-64]. If the humidity is constant, an increase in the temperature will increase the rate of chemical reaction. Nevertheless, the effect of temperature on atmospheric corrosion is actually complex. Increase in the temperature will tend to increase the electrochemical and diffusion processes, thereby increasing the corrosion rate of exposed carbon steel material.On the other hand, increasing the temperature will also decrease the humidity and increase the evaporation surface electrolyte from the exposed steel surface [64]. Yin et al. [65] examined the effect of temperature on corrosion of carbon steel. Different characterisation techniques were used to analysis the corrosion product formed on the carbon steel surface. The result showed that the corrosion layers formed at higher temperature between 150 and 180° were different from the layers formed below 130°. Another interesting report from the result was that the average temperature was much higher at 50°C compared to other temperatures. In coastal environment, the effect of temperature on carbon steel may be difference as the humidity and temperature are high in most part of the year. Matsunami et al. [2] investigated the corrosion behaviour of carbon steel in the presence of aqueous sulphide at different temperatures using the dynamic-immersion test, static-immersion test, and weight loss techniques. The result showed that corrosion behaviour of carbon steel depends significantly on the temperature at different sulphide concentrations (Figure 6).

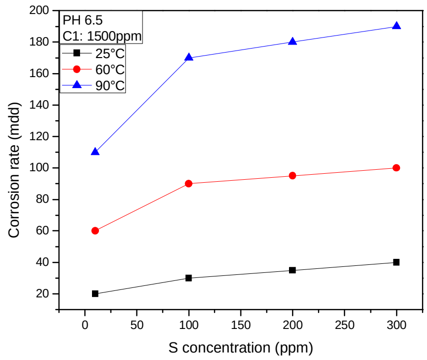

Figure 6:Effect ofTemperature on the Corrosion of Carbon Steel at Different Sulphide Concentrations [2]

In a similar study,Neshati et al. [66] investigated the corrosion behaviour of carbon steel at environmental temperature range between 35 °C and 45 °C. Electrochemical techniques and weight loss techniques were employed in the analysis of the results. The results revealed that the presence of sulphur plays a critical role in the formation of the sulphide film observed during corrosion of pipeline system and can be more aggressive in the combination of other parameters [67]

Effect of Location and Exposure Time on the Corrosion of Carbon Steel

Exposure time plays critical role on the life of pipeline carbon steelwhen exposed to the environmentand can vary between locations[58, 68]. In a corrosive environment, the longer the steel material is exposed to the corrosive environment, the more destructive willbe the carbon steel with time. Katayama et al. [69] investigated the atmospheric corrosion behaviourof carbon steel, comparing the outdoor environment and in-chamber conditions. Temperatures of carbon steels and relative humidity of the chamber were control throughout the tests. The result showed similar corrosion behaviour of carbon steel in both atmospheric and sheltered environmental conditions (Figure 7). However, the corrosion appear more severe on the carbon steel sample tested in the actual atmospheric condition as the exposure time was

increased from 1 to 10days (Figure 7), underlining the importance of environmental factors on corrosion of carbon steels.

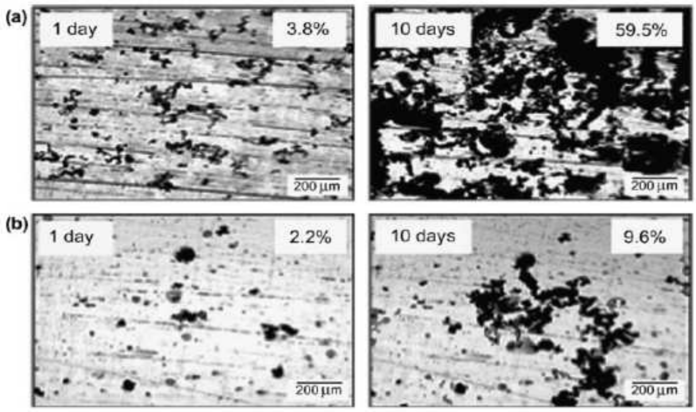

Figure 7: Optical Micrographs of the Surface of Carbon Steels after the Corrosion Test in Actual Environment (A) and Chamber (B). Corrosion Simulation was Conducted in Chamber by Controlling Temperature and Relative Humidity Based on Meteorological Data [69]

The result also revealed that dew condensation and other environmental factors near the sample surface influenced the initial corrosion of the carbon steel, but subsequent reaction did not affected the carbon steel significantly. The authors suggested that oxide films were the corrosion products found on the exposed carbon steel surface and the rate at which the films are formed is influenced by environmental factors and surrounding medium[68]. Change in the environmental factors and other parameters can as well influence the oxide film formation. Allam et al. [70] studied different stages of corrosion product development on carbon steels exposed to atmospheric condition in the Gulf Arabia region. Several characterisation techniques were used to study the corrosion products found on the carbon steel exposed to atmosphere for 12 months. The result revealed that corrosion started with formation of small blisteron the carbon steel surface with preference at the anodic position. Further analysis of the corrosion products showed that the blisters were rich in hydroxide, oxyhydroxides, oxides and sulphates. The formation of the oxide and sulphide could be a function of concentration of the environmental factors of the given location and sample chemical composition. However, for the newly develop high carbon steel grades with additional alloys, the interaction between the carbon steeland the atmospheric sulphur dioxide might be different and may require further study and review.

CONCLUSIONS

Although some of the environmental factors have been discussed in the literature, relationship between these factors and the carbon steels used as pipeline materials has not been detailed. Experimental knowledge–based studies have contributed in the understanding of the corrosion process. However, review of these studies done in this field need to be examined and correlation between the processes outlined. The following can be concluded from the study.

- Environmental factors affect the corrosion of pipeline carbon steel especially in the coastal areas.In coastal regions, the humidity is relatively high with contaminated environmental pollutants which influence the corrosion of carbon steel exposed to the atmosphere.
- The presence of hydrogen sulphide can induce non-protective iron sulphide on the carbon steel surface, thereby increasing the corrosion rate of pipeline carbon steel exposed to atmosphere.

- Chloride ions from sea water influence the salinity of the atmospheric corrosion medium. This condition provides a corrosive condition for corrosion of pipeline system.

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